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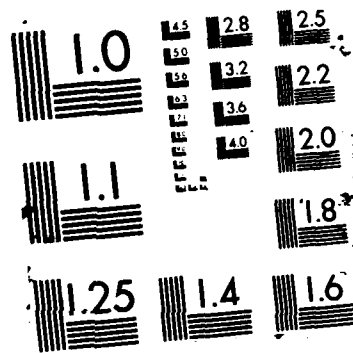
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Superconducting Switch Program

T.L. FRANCAVILLIA, S.A. WOLF AND D.U. GUBSER

*Metal Physics Branch
Condensed Matter/Radiations Science Division*

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| <p>The NRL Superconducting Opening switch program for 1985 to 1986 is reviewed. The results of material studies to determine sputtering parameters is presented along with preliminary switching studies to determine switching speed. The investigation is continuing.</p> | | | | | |
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SUPERCONDUCTING SWITCH PROGRAM

This is an interim report on continuing work to study the feasibility of a thin film superconducting opening switch. This phase of the investigation addresses three areas:

1. The optimization of switching parameters of niobium nitride thin film switches by controlling sputtering deposition parameters such as substrate temperature, argon gas pressure, etc., so that the normal state resistivity and the superconducting critical current density are a maximum.
2. The determination of laser induced switching speed.
3. The investigation of switching mechanisms.

(1.0) Optimization of material parameters

Many deposition parameters affect the superconducting and normal state properties of these metal films. These include rf power, target substrate separation, target bias, inert gas pressure, reactive gas to argon ratio, substrate temperature etc. While some of these parameters are not independent, e.g. the amount of reactive gas in the chamber affects the target bias voltage and the deposition rate, some are more important than others in their effect on film properties. In our experience these are temperature, pressure, and reactive gas to argon ratio. NbN and some NbCN films were prepared under conditions which were systematically varied while their effects on the superconducting and normal state parameters were measured. Substrate temperature was felt to have the most dramatic effect on film properties so

this was the first quantity to be varied. The argon pressure was thought to have the second most important effect so this was examined next. This was done in two steps. First the effect of temperature on the ρJ_c product was optimized. Using this value of substrate temperature the effect of pressure on the ρJ_c product was then optimized.

In both instances the ratio of reactive gas to argon was kept low. That is to say, only a small amount of reactive gas was added to the argon for sputtering. This was done continuously to replenish that consumed during the sputtering process. Past experience has shown this gave material with the highest sputtering rate so it was felt to be a good starting point. The effects of varying temperature and pressure during the preparation of niobium nitride are shown in the next section. Higher reactive gas ratios are also being explored since these have been known to bring about changes in texture. Preliminary measurements for the condition of high reactive gas ratios will be discussed later in this report.

For our earlier studies we also prepared niobium carbonitride by mixing cyanogen with nitrogen to form our reactive gas mixture. Niobium carbonitride has a slightly higher transition temperature and a much higher melting point so it was interesting to see how this material would perform in a switch application. We found slightly better properties for this application but also noted that the variations for this material with preparation conditions tracked those of niobium nitride. Consequently it was felt that there was little advantage to a parallel study of both materials and optimizing one would give an optimum for the other. When an optimum condition for niobium nitride is arrived at varying one parameter (e.g. argon pressure), the reactive gas mixture may then be changed to a nitrogen cyanogen mixture to make the carbonitride.

(1.1) Optimization for substrate temperature; pressure and mixture constant

Transition temperature measurements were made by measuring the change in resistance of the film as a function of temperature. The midpoint of the transition was taken as T_c . Transition temperature gave us some idea about the quality of a particular film since this measurement is sensitive to impurities. A high transition temperature also gives an indication of the temperature range over which a device made using such a film would be useful.

Figure 1 shows the effect of substrate temperature on transition temperature for both niobium nitride and niobium carbonitride. The argon pressure was constant at 60 mtorr. For substrate temperatures ranging from ambient to 800°C, transition temperatures increased from 10K to 16.9K.

The critical current density was measured by immersing into liquid helium a film which had been patterned into an H shape using standard photo-lithographic techniques. The horizontal part of the pattern was one sixteenth of an inch wide. This kept the values of current down into a range that was easy to measure. Current was introduced into the vertical part of the H pattern and increased until the film was catastrophically driven normal. The value of current at this point was taken to be the critical current.

Figure 2 is a plot of critical current density as a function of substrate temperature for constant argon pressure of 60 mtorr, including both niobium nitride and niobium carbonitride films. For substrate temperatures ranging from ambient to over 800°C, critical current densities ranged from 3.45×10^4 amps per square centimeter to 8.02×10^5 amps per square centimeter.

The resistivity of interest is that value at low temperature (20K) just above the transition. This determines the resistance of the switch in the open or normal state and fixes the amount of current diverted to a load as well as the dissipation when the switch is open.

Figure 3 is a plot of resistivity versus substrate temperature, including both niobium nitride and niobium carbonitride. For a broad range of substrate

temperatures, approximately 300°C to 800°C, the resistivity is approximately constant between 500 to 2000 micro ohm cm. Below 300°C, the resistivity rapidly jumped to about 7000 micro ohm cm. Above 800°C, the resistivity fell to about 100 micro ohm cm.

The product of the critical current density resistivity is taken to be a measure of the quality of the device, and as such is the quantity to be optimized for this study. Combining the results of Figures 3 and 2, we arrive at Figure 4 the required product as a function of substrate temperature. The data shows a maximum at about 650°C. The maximum value was 730 volts per cm for a niobium carbonitride film that inadvertently was contaminated with a few percent of oxygen. The highest value of NbN in this series was 445 volts per cm. These data show a considerable amount of scatter which is a reflection of the critical current density.

(1.2) Optimization for argon pressure; substrate temperature and reactive gas increment constant

The variation of substrate temperature indicated that a maximum occurs at a value of 650°C. Using this value which is now held constant the argon pressure was then varied in search of a further optimization of the J_C product.

Figure 5 is a plot of the superconducting transition temperature of NbN as a function of argon pressure for substrate temperature held constant at 650°C. The transition temperature is seen to increase with decreasing argon pressure, from 12K at 60 mtorr to 16K at 15 mtorr. This is interesting in its own right and could impact on other device work because of the low substrate temperature used during deposition.

Figure 6 is a plot of the critical current density as a function of argon pressure with the substrate temperature held constant at 650°C. The data show a slow variation of critical current density centered around 2.0×10^5 amps

per square cm for argon pressure from 60 mtorr to 30 mtorr with an increase to 7.0×10^5 amps per square cm at the lowest pressure.

The resistivity as a function of argon pressure for constant substrate temperature is shown in figure 7. The resistivity increases rapidly from 224 micro ohm cm at 15 mtorr to about 2,500 micro ohm cm at 30 mtorr, and then slowly increases to 3,000 micro ohm cm.

Combining the above data to arrive at the ρJ_c product in Figure 8, we find a maximum of approximately 780 volts per cm at an argon pressure of 45 mtorr with ρJ_c falling off at higher and lower pressures. This value of 780 volts per cm is a large increase for NbN from the value of 445 volts per cm obtained in the temperature variation study described earlier.

(1.3) Optimization of reactive gas ratio; substrate temperature and argon pressure held constant

The reactive gas to argon ratio has been shown to affect the texture of a NbN and NbCN thin film. The question is whether or not this texture will favorably affect the ρJ_c product of the material, and so enhance the parameter of a superconducting opening switch made from this material. In the pressure variation study, there is some ambiguity with regard to the parameter which is held constant namely the total pressure, (argon plus reactive gas) or the argon pressure only being held constant (with the reactive gas being added above this constant value). In order to explore these alternatives two series of films were prepared. In the first series the total gas pressure was held constant, with the argon pressure decreasing as the nitrogen pressure increased. In the second series, argon pressure was kept constant and increasing amounts of reactive gas were added to the sputtering chamber.

In the first study, the films were found to be increasingly thin. The deposition rate fell drastically as the reactive gas to argon ratio increased. Preliminary measurements were made and the resultant low ρJ_c product values indicate that probability of an improvement are small. Consequently this line

of investigation will not be pursued further unless more encouraging results are forthcoming.

In the second study, high argon pressure guaranteed that sputtering rates remained high but these conditions also produced films whose ρJ_c product were inferior to those made under other conditions, and will not be pursued unless more encouraging results are found.

(1.4) Addition of oxygen

The addition of small amounts of oxygen (2.5%) to the nitrogen reactive gas has been found to have the effect of increasing the sheet resistance without significantly decreasing the transition temperature. The best film obtained in this instance was a NbN film 0.8 microns thick. It has a T_c of 14.2K, a critical current density of 4.46×10^5 amps per square cm, and a ρJ_c product of 902 volts per cm. This is a substantial improvement from the early value of 445 volts per cm. We intend to explore the variation of oxygen concentration to see if an optimum can be found.

(1.5) Collaboration with other groups

We have been in contact with scientists at Argonne National Laboratory. They have supplied us with films and we have measured their ρJ_c product. These values were 827, 582, and 51 volts per cm. In choosing the sputtering conditions for these specimens, an attempt was made to span the range of sputtering conditions available to produce a large ρJ_c product. We will be in further contact with them. Perhaps the addition of oxygen to their system during the sputtering process will have the same beneficial affect.

We have also sent samples with widely varying ρJ_c values to scientists at Sandia National Laboratory for electron microscopy studies. Initially we are looking for large features but ultimately if these initial studies prove to be successful we would look to see if changes in the microstructure could be related to the measured properties.

(2.0) Switching speed

We have made some preliminary measurements on the switching speed of a laser activated switch. In these experiments a superconducting film was connected in parallel with a room temperature normal state load. The film was driven normal with a laser pulse and the current was diverted into the load. Initially 20 amps was switched with a rise time of less than 20 ns, and a pulse half-width of approximately 50 ns. In subsequent experiments currents of up to 30 amps were switched but these were non-repetitive. Once they were activated they did not recover to the superconducting state while they were carrying current. At lower currents when the switch did not latch-up, the switching times were on the order of microseconds.

The problems encountered in this experiment were not fully understood. They might be related to the spatial inhomogeneity of the laser pulse giving rise to a hot spot which took time to propagate along the film and ultimately drive it normal. Apparently this was not a problem on more metallic films. We believe that more extensive laser testing is necessary in the light of the test data obtained so far. We have a good understanding of what parameters to adjust to tailor the characteristics of a film switch now that the basic sputtering parameters have been surveyed and correlated with the superconducting and normal state parameters.

(3.0) Switching mechanisms

The method by which the film switches from the superconducting to the normal state and back to the superconducting state is currently thought to be a thermal process. Experiments to demonstrate this will be undertaken but up to now have taken second place to determining conditions important to depositing films, with properties favorable for a superconducting opening switch.

(4.0) Summary

In summary, we have explored the preparation conditions necessary to produce films with a high ρJ_c produce and have learned how to tailor films to have specific properties. We have begun collaboration with scientists at Argonne and Sadia Laboratories. We have made preliminary laser measurements and feel that more careful laser testing is now in order.

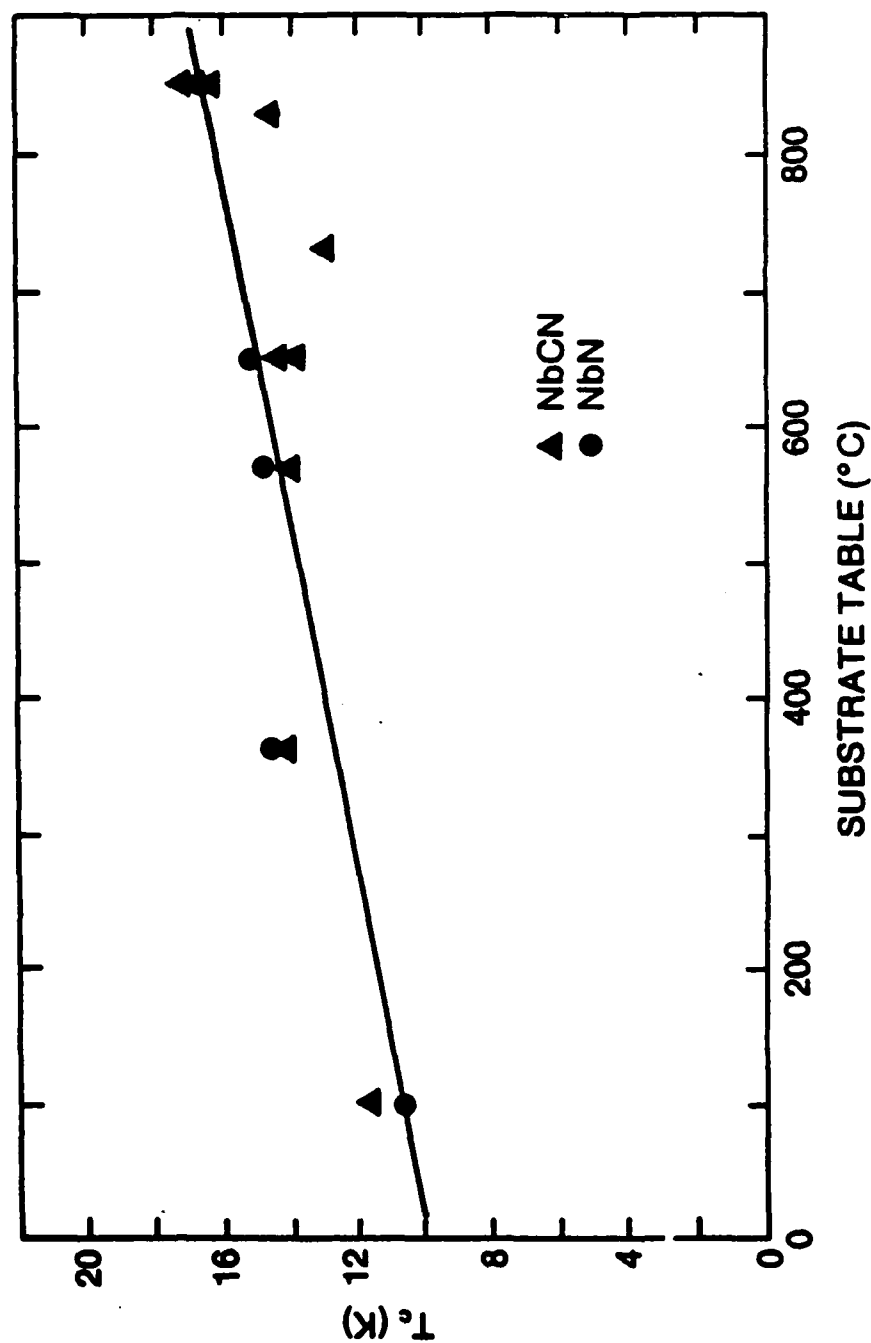


Figure 1. Transition temperature of NbN and NbCN films plotted as a function of substrate temperature during sputter deposition. Argon pressure was 60 mtorr and reactive gas was 3 mtorr (argon to nitrogen ratio for NbCN was 20:80).

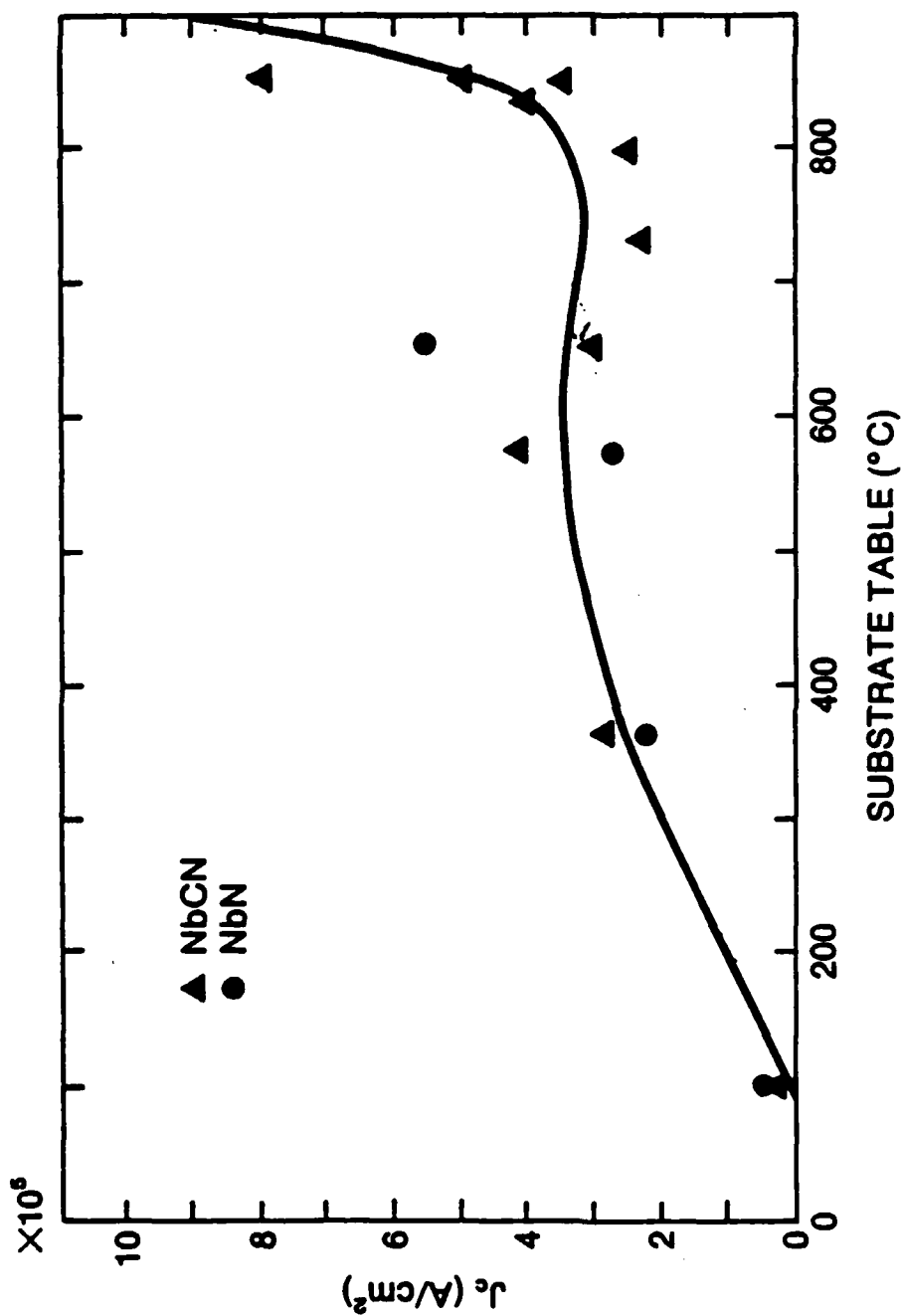


Figure 2. Critical current density of NbN and NbCN films as a function of substrate temperature during sputter deposition. Argon pressure was 60 mtorr and reactive gas was 3 mtorr (canogen to nitrogen ratio for NbCN was 20:80).

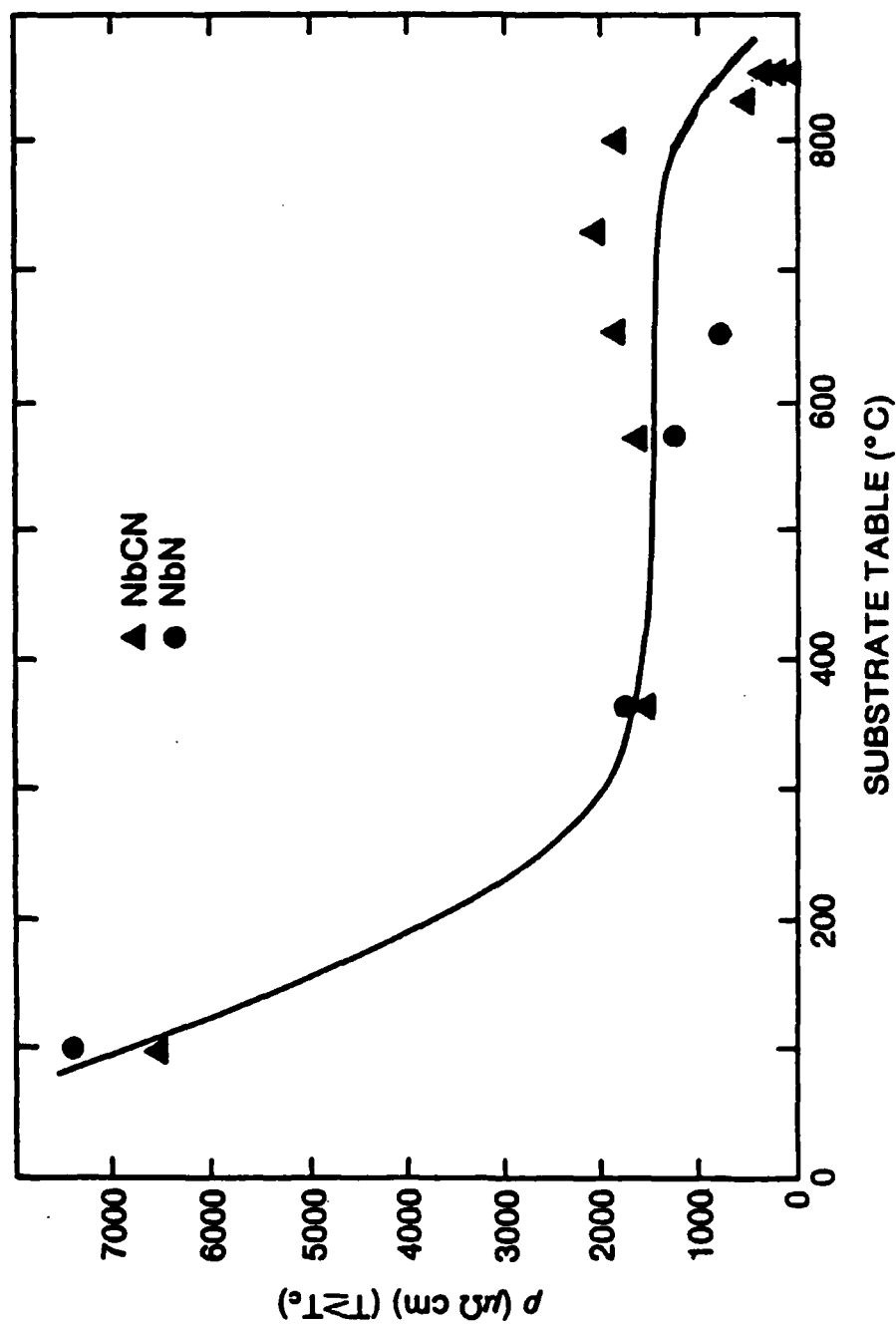


Figure 3. Resistivity of NbN and NbCN films as a function of substrate table temperature during sputter deposition. Argon pressure was 60 mtorr and reactive gas was 3 mtorr (cyanogen to nitrogen ratio for NbCN was 20:80).

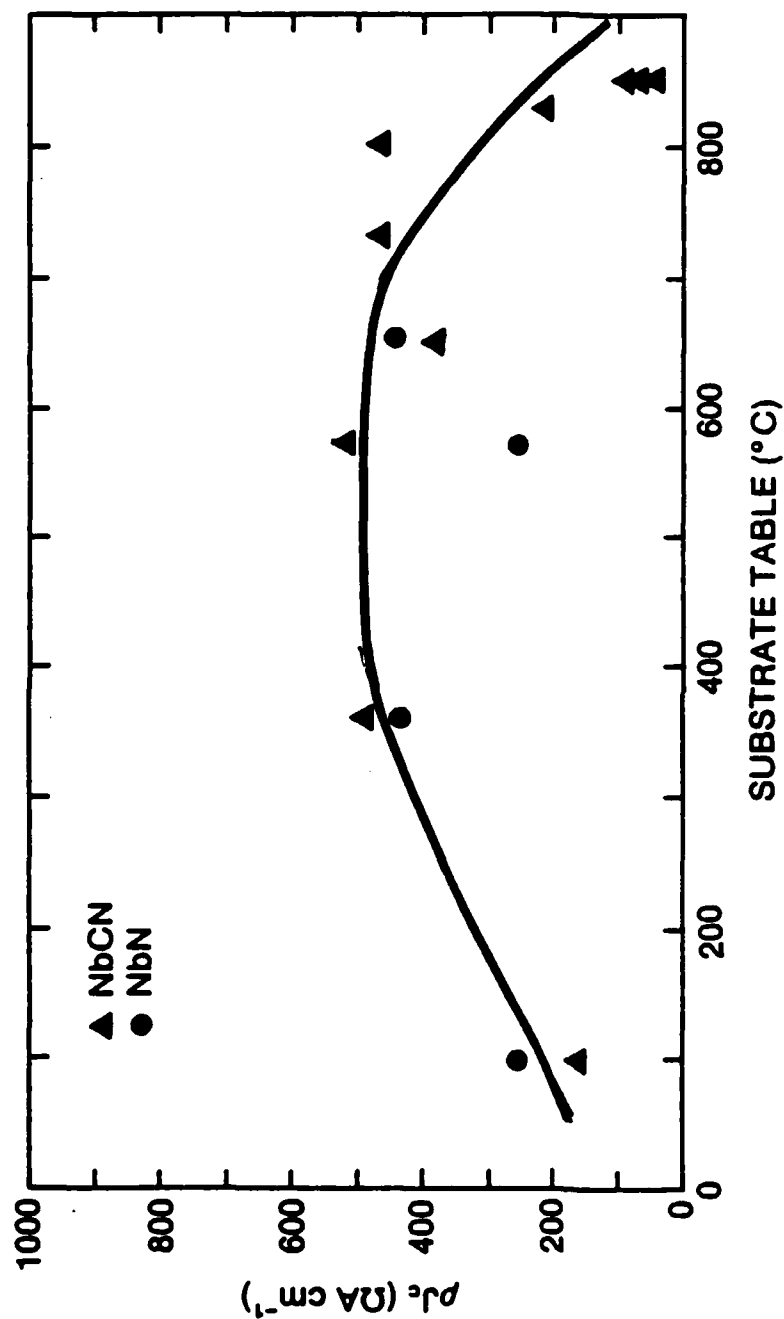


Figure 4. RJ_c product as a function of substrate table temperature using data of Figures 2 and 3. A maximum is seen to occur at approximately 650°C .

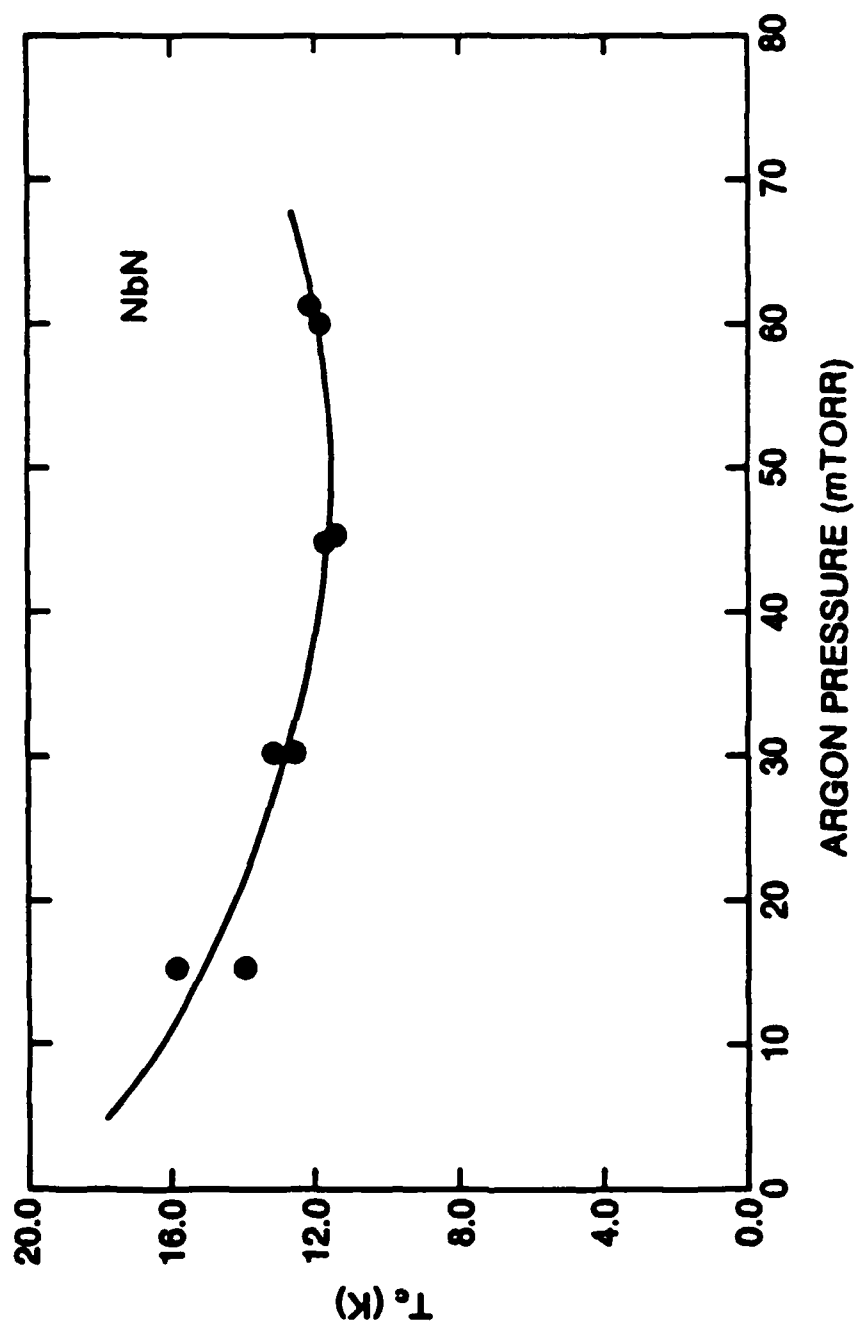


Figure 5. Transition temperature as a function of argon pressure for NbN films. Substrate temperature was held at 650°C. Reactive gas (nitrogen) was 3 mtorr above the ambient argon pressure.

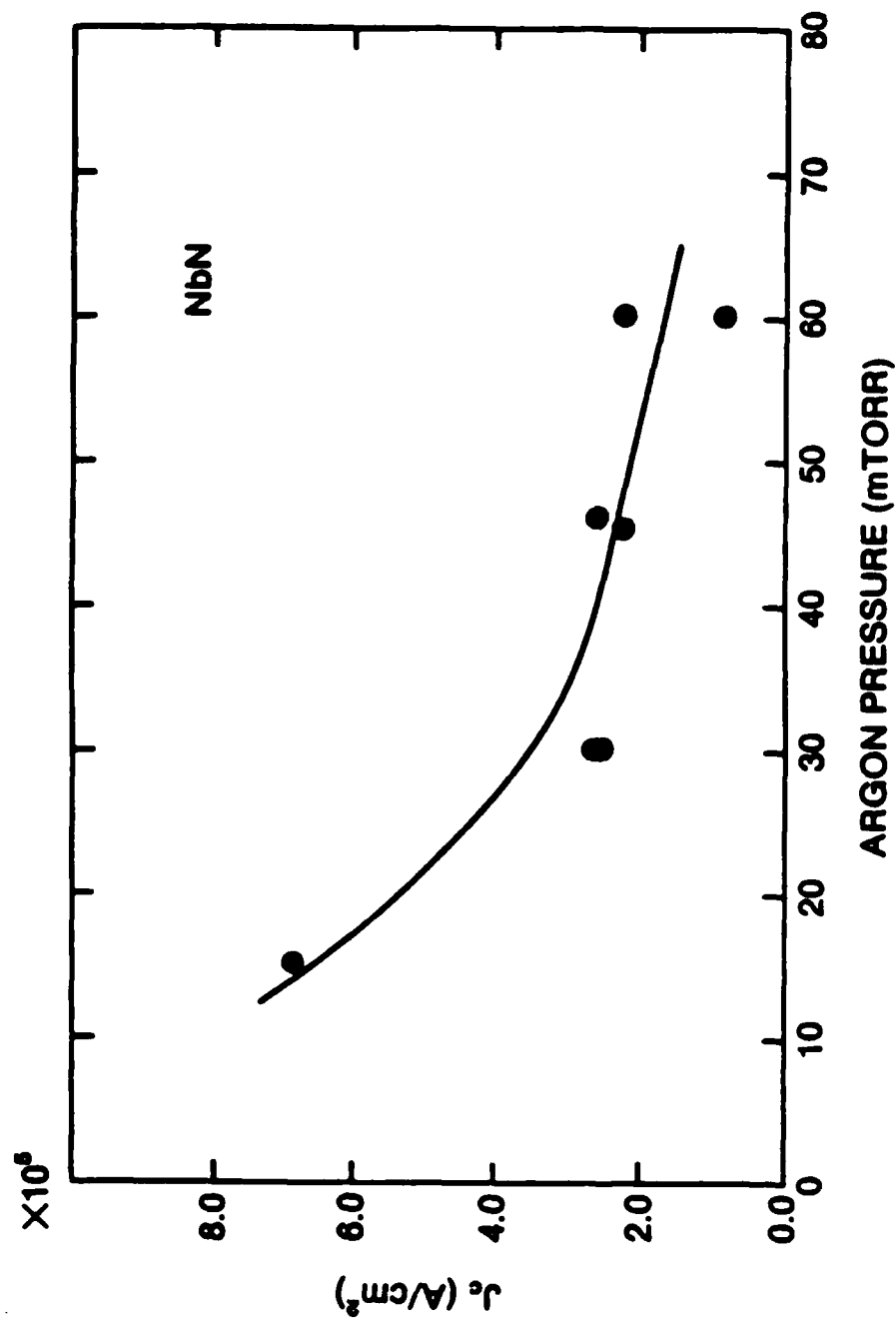


Figure 6. Critical current density as a function of argon pressure for NbN films. Substrate table temperature was held at 650°C. Reactive gas (nitrogen) was 3 mtorr above the ambient argon pressure.

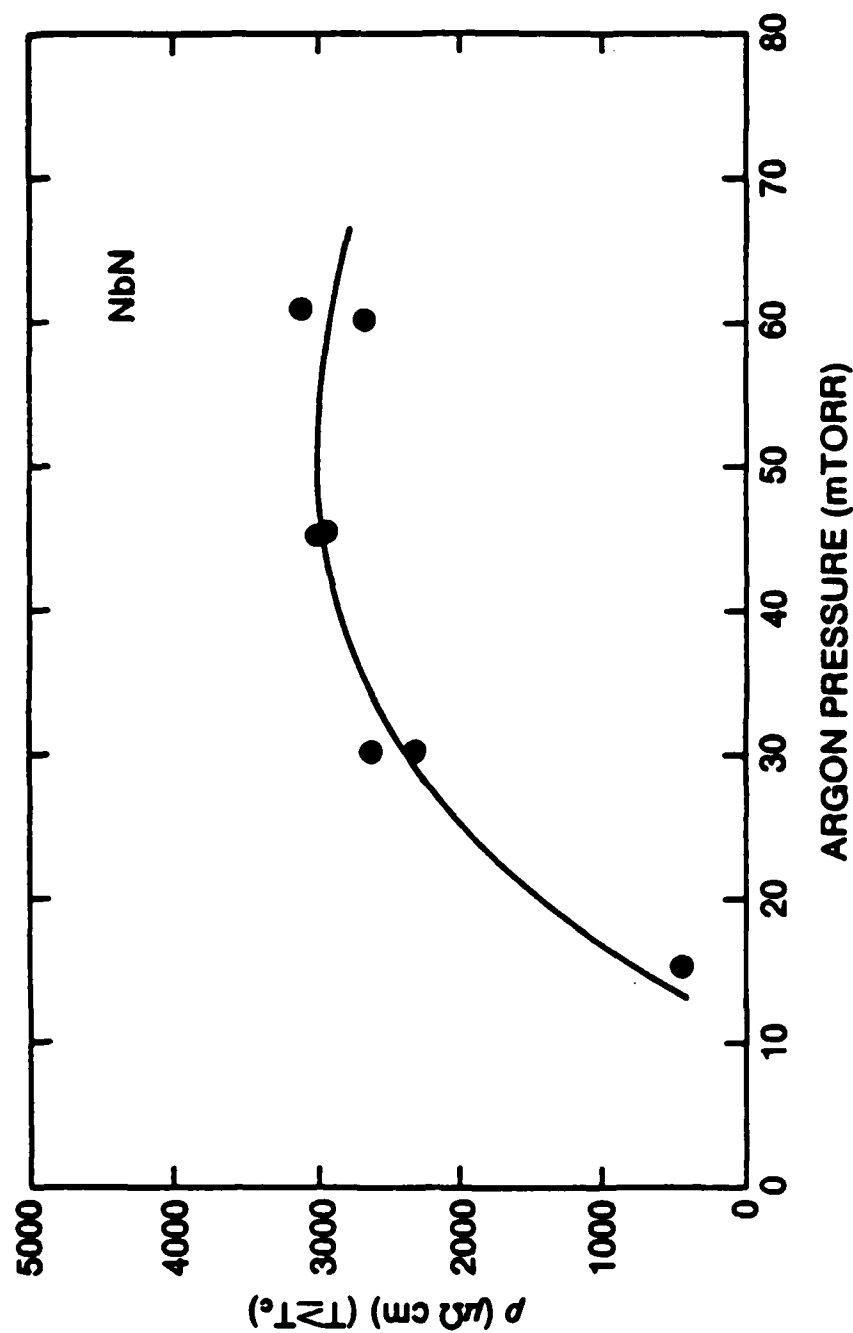


Figure 7. Resistivity as a function of argon pressure for NbN films. Substrate table temperature was held at 650°C. Reactive gas (nitrogen) was 3 mtorr above the ambient argon pressure.

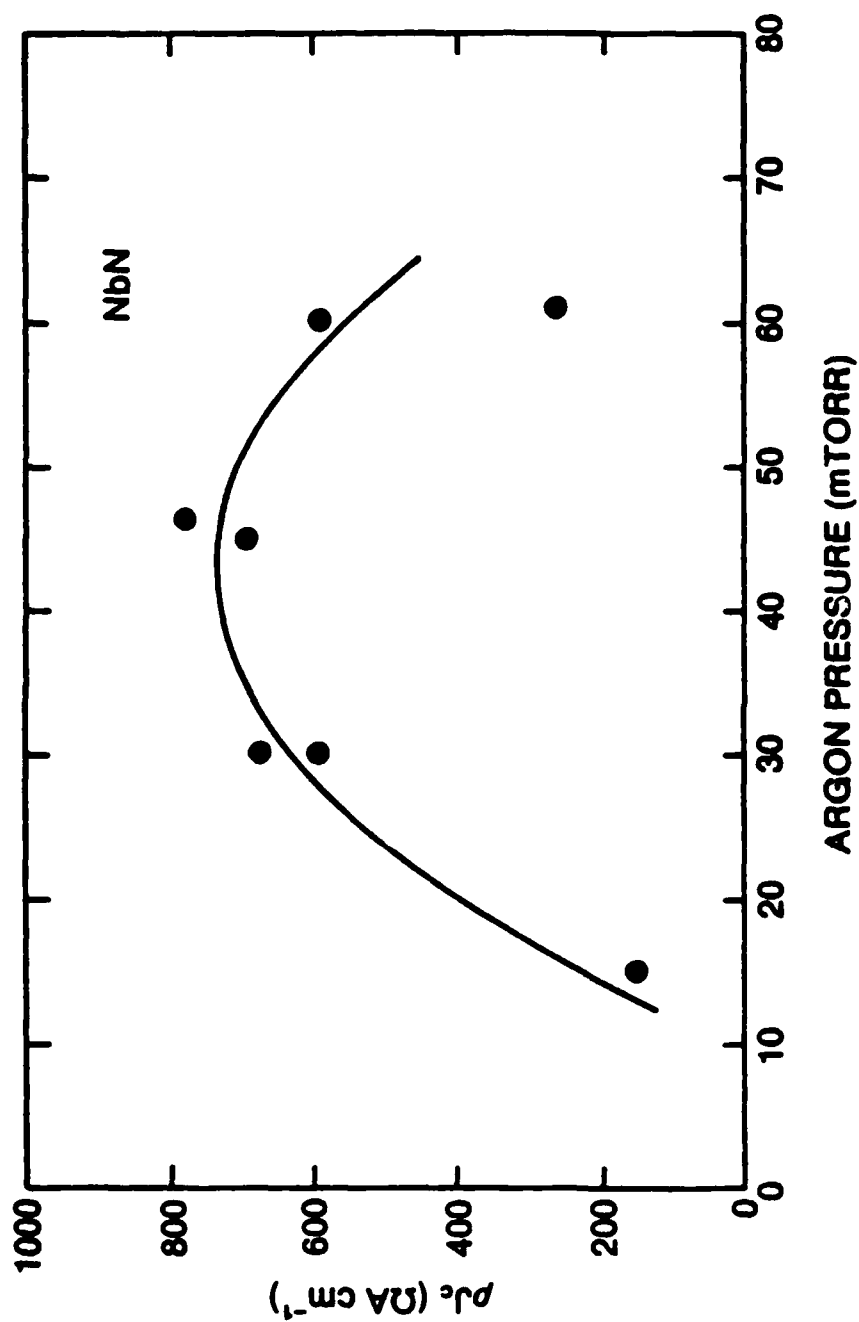


Figure 8. RJ_c product as a function of argon pressure using the data of figures 6 and 7. A maximum is seen to occur around 45 mtorr. The filled square shows the NbN film made with 2.5% oxygen for comparison.

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